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Comparison of progressive collapse resistance of single-layer latticed domes under different loadings

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ABSTRACT

Progressive collapse tests of two single-layer latticed Kiewitt domes were conducted in this paper. In each dome, one meridian member was suddenly removed and the full field structural responses, including high-speed 3D joint displacements and high-frequency member strains, were collected. Results of the test program and the corresponding FE analysis show that: (1) The tested dome under smaller loads regained balance easily, while a snap-through collapse occurred for dome under larger loads. Hence, although a single-layer latticed dome is normally constructed with hundreds of structural members, progressive collapse of the whole structure can be caused merely by the loss of a single critical member; moreover, load-resistance redundancy of a single-layer latticed dome is crucially important in resisting progressive collapse. (2) The sudden removal of a member caused a non-significant impact on the overall compressive membrane force flow but resulted in severe structural damage at the end-joints of the removed member; if the local damage was not properly absorbed, point buckling would occur on one of these two joints and was regarded as the immediate cause of the progressive collapse. (3) The collapse mode of a single-layer latticed dome subjected to sudden member-loss was characterized by a totally snap-through collapse; the collapse started from the point-buckling joint and was caused by successive downward movements of the surrounding joints. (4) Finite-element analysis provides an efficient way for progressive collapse study of dome structures, but fracture criterion of constructional steel that considers the complex stress states during progressive collapse is still needed.

1. Introduction

Progressive collapse is a chain reaction type of failure initiated by loss of one or a few load-carrying elements. Since the collapse of the World Trade Center towers in 2001 [1], comprehensive studies have been conducted to investigate the performance of buildings subjected to local failure from abnormal events. Most of these studies, whether by employing numerical methods [2–6] or by means of experimental approaches [7–10], have focused on the collapse resistance of frame structures. All the currently available codes and guidelines for structural design against progressive collapse [11–14] mainly target frame structures. By contrast, progressive collapse studies on space structures which refer to large-span roofing systems covering large open areas are very limited. This situation may be resulted from the fact that some historic collapsed buildings including the afore-mentioned the World Trade Center towers were all frame structures. The intuition that the loss of a single member (or a few members) can cause only limited damage in a space structure which has excellent degree of redundancy provided by the densely arrayed structural members also accounts for the lack of attention to large-span roofing failures [15].

Progressive collapse events of large-span space structures, however, have been reported more frequently as their construction rate rises. In 2006 alone when the continent of Europe suffered from abnormally cold winter conditions, three catastrophic roof collapse events were reported: the collapse of the Bad Reichenhall ice rink roof killed 15 people and injured 34 people; the collapse of the Katowice trade hall roof caused 65 fatalities and over 170 injuries, and the collapse of the Moscow Basmanny market roof caused 66 fatalities. The collapse events were directly induced by the overloading conditions caused by heavy snow or rain. Nevertheless, the incapability of establishing an alternate path in the remaining structure of each roof, which could have absorbed the local failure is also responsible. In order to prevent such catastrophic incidents, there is an urgent demand for studies on the collapse resistance of large-span space structures following local failure.

So far, studies on the progressive collapse performance of space structures have mainly focused on the truss-type structures. These studies were carried out by means of the Alternate Path (AP) method, in which a load-bearing element was suddenly removed to evaluate the general integrity of the structures and their capacities in redistributing the loads following severe damage. Although truss-type structures are

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known for their large degree of redundancy, Murtha-Smith et al. [16], Malla et al. [17], and Jiang et al. [18] showed by employing finite-element (FE) methods that progressive collapse can occur following the potential loss of a single critical member. Zhao et al. [19] and Yan et al. [20] studied the collapse resisting mechanisms of planar trusses through experimental, numerical and analytical approaches and confirmed the existence of catenary action and arch action in planar trusses subjected to sudden member loss.

Latticed dome is another commonly used large-span space roofing system which carries the external loads through a spatial action. This is very different from the planar trusses or truss structures that are constructed by tying several planar trusses through purlins, and thus the potential collapse resisting mechanism of the latticed dome can be different from that of the truss structures. Han et al. [21] evaluated the progressive collapse potential of latticed domes with a span over 100 m by means of the FE method, and demonstrated a better collapse resistance of the double-layer latticed domes over the single-layer latticed domes. However, to the best of our knowledge, no experimental research regarding the progressive collapse resistance of such structures has been reported yet. As physical tests are indispensable in studying the accurate nonlinear behavior of structures in collapse scenarios and providing benchmark data for validating the FE results, there has been a great need for experimental studies on the progressive collapse of latticed dome structures.

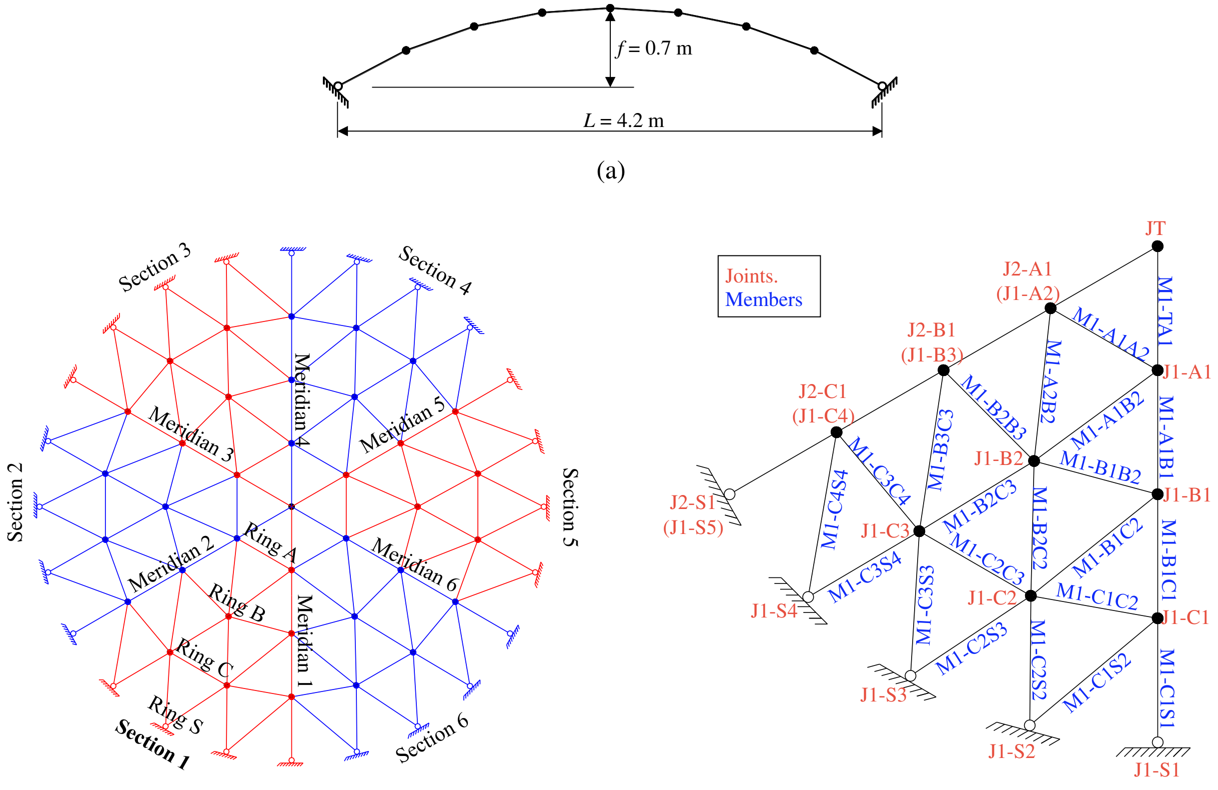
This paper presents a comprehensive experimental study on the dynamic progressive collapse resistance of single-layer latticed domes. Two Kiewitt domes were tested by suddenly removing one of the meridian members. The two tested domes were entirely identical, i.e., sharing the same geometric, material properties and the same joint construction, but were subjected to different applied loads. The first dome (referred as dome-0.4) was loaded with a point load of 0.8 kN at each joint, while for the second dome (referred as dome-0.75), the point load was 1.5 kN. Therefore, by comparing the two tests, the collapse resistance mechanism of the single-layer latticed domes can be revealed, and the significance of load-resistance redundancy can also be demonstrated. Furthermore, the tests and associated analysis contribute to establishing a database of benchmark models for space structural systems for future numerical and parametric studies.

2. Test program

2.1. Specimens

Two Kiewitt domes, designed according to Chinese Code for Design of Steel Structures (GB50017) [22] and Chinese Technical Specification for Space Frame Structures (JGJ 7) [23], were carefully prepared and tested. Fig. 1a and b shows the geometric properties of the tested domes. With a constant span of 4.2 m and a span-rise ratio of 7, each dome had six meridians and thus was divided into six identical sectors. There were four rings, the positions of which were determined by equally dividing the meridians on the horizontal projection plane to ensure identical point loads at all joints in the testing program, where the symmetric roof loads were simplified as concentrated point loads at all joints. All edge joints were made as supports fixed on the strong substructure such that the outermost ring (ring S) members were not needed.

In total, there were 132 members, 37 joints and 24 edge supports in each tested dome. They were all labeled for convenient interpretation of the experimental program. Fig. 1c shows the labeling system in Sector 1. A joint or an edge support in this sector starts with J1 (J1 denotes joint in Sector 1) and is followed by the position of the joint or the edge support in this sector (according to the ring where it is located and its position on the ring). A member in this sector starts with M1 (M1 denotes member in Sector 1) and is then labeled according to the end-joints of this member. Joints and edge supports in Sector 2 start with J2, and members in Sector 2 start with M2, and so on.



(a)

(b)

(c)

Fig. 1. Overview of the tested domes. (a) view of the meridian section; (b) view of the horizontal projection plane; (c) labeling of joints, edge supports and members in Sector 1.